SHORT ARTICLES AND REVIEWS

THE ENVIRONMENTAL REQUIREMENTS OF SALMON AND TROUT IN FRESH WATER

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Introduction

In recent years a number of books and research papers have brought together much of the available information on environmental requirements of salmon and trout. General information on salmon is given by Le Cren (1984), and for trout information is given by Le Cren (1985), Elliott (1989) and National Rivers Authority (1991). Solbe (1988) is a valuable summary of the water quality requirements of salmon and trout but is slanted towards chemical pollutants. Further useful information is included in Mills (1992). The Salmon Advisory Committee (1991) produced a report on factors affecting natural smolt production of Atlantic salmon. This document is of patchy quality and appears to contain some material which is well documented in peer-review literature and some which is not.

The present article is not an in-depth review. Rather it is a summary for the general reader, though every effort has been made to ensure that the information used is of a high scientific standard.

The article attempts to define, as quantitatively as possible, the habitat requirements of salmon and trout and then to relate them to the main ways in which man's activities can influence the survival and growth of these fishes.

Recent years have also seen a marked increase in our quantitative knowledge of the environmental requirements of various life-stages of common salmonid fishes, and the information given below rests upon a substantial base of research findings. Frequent text references to this extensive body of published work have been deliberately avoided in this article. However, a selective bibliography has been included and this lists some of the main work upon which the text depends.

This article deals only with the freshwater part of the life cycle, though conditions and events in estuaries and the sea can have an important influence on salmon and sea-trout. There is some bias in the coverage towards Britain and, indeed, towards England and Wales.

British salmonids and their life cycle

The term "salmonid" refers to fishes of the family Salmonidae. For present purposes the grayling *(Thymallus thymallus* (L.)) is assumed to belong to the family Thymallidae (after Maitland 1977 and Maitland & Campbell 1992) rather than being included in the family Salmonidae (as in Wheeler 1992). Three species are indigenous to the British Isles: Atlantic salmon *(Salmo salar* L), trout *(Salmo trutta* L.) in both its resident (brown trout) and sea-going (sea-trout) forms, and Arctic charr *(Salvelinus alpinus* (L.)). In addition, rainbow trout *(Oncorhynchus mykiss* (Walbaum)), American brook charr *(Salvelinus fontinalis* (Mitchill)), and possibly humpback salmon *(Oncorhynchus gorbuscha* (Walbaum)), occur as introductions. The first of these is widespread in Britain and elsewhere as an escapee from fish farms and stocked fisheries.

All of these species show a number of similarities in their environmental requirements. However, in the following account the term "Salmonidae" will primarily refer to the two widespread British species — Atlantic salmon and trout — and, where appropriate, quantitative information will refer to each species individually.

Spawning of salmonids

The female parent selects a place where there is clean, running water and silt-free gravel of a suitable type. She excavates a pit in the streambed. She does this by turning on her side and then, with swimming-like movements of her body, she creates suction which lifts the gravel off the bottom to form a pit. This gravel is displaced a little downstream by the current. At intervals she "tests" the pit by lowering her anal fin into its bottom; apparently this is done to assess the flow of water through the gravel below the pit. When satisfied, she deposits eggs in the pit and the male fertilises them with his sperms ("milt"). The female then digs another pit upstream of the first one and the spoil from the second pit covers the eggs in the first pit. This process continues until one or more pockets of eggs are produced within an oval structure called a "redd" (Fig. 1). A female may dig one or more redds during the course of a spawning season but the most usual number is one per female. If a pit is dug and the female finds it unsatisfactory, she will move off and make a redd elsewhere, leaving behind a "false redd" or "trial scrape".

Salmon and trout spawn during autumn and winter. In upland and northern areas with a more severe climate, spawning occurs mainly

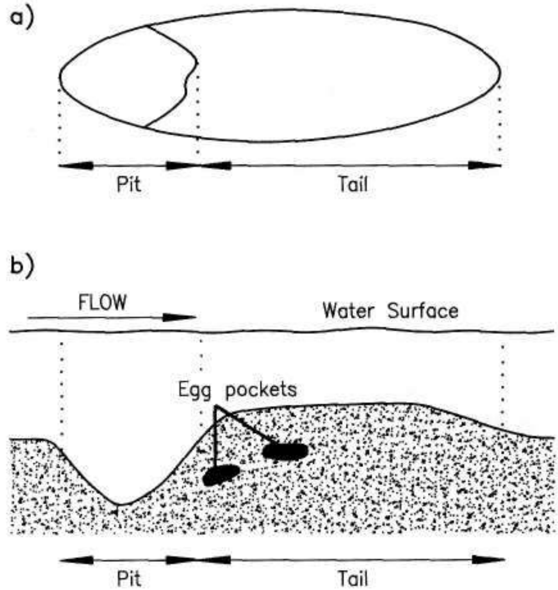

FIG. 1. Plan view (a) and longitudinal section (b) of a redd.

between October and December and may be confined to a period of only two or three weeks, whereas in areas with less severe conditions the spawning period may be later (November to March) and extend over several months. Within any given river the trout tend to spawn earlier than the salmon, and trout make more use of small headstreams as spawning sites. Spawning trout (even quite large sea-trout) can sometimes be found in streams less than 50 cm wide.

Salmonid eggs and alevins

The period of life within the gravel extends from the time when the egg is laid to the time when the "alevin" emerges from the gravel and becomes a "fry" (Plates 1 and 2, facing pp. 188 and 189). Three important events can be recognised in the process of intragravel development. After some time the eye pigment of the embryo becomes visible through the casing of the egg. This event is known as "eyeing". At a later stage the egg hatches into an "alevin" (Plate 1). The alevin remains in the gravel and subsists on its yolk sac. When the yolk sac is almost exhausted the alevin emerges from the gravel, acquires pigmentation in its skin, fills its swim bladder with air

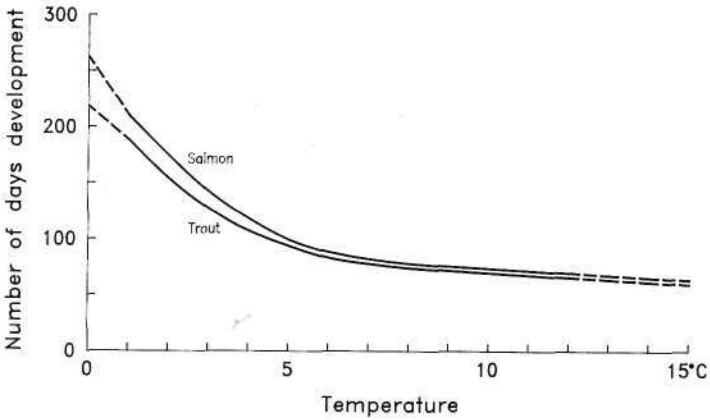

FIG. 2. The number of days required to attain median hatch for trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) at different temperatures. The solid lines cover the range of observed values and the broken lines are extrapolations.

so as to attain neutral buoyancy, and begins to take external foods. This event is termed "swim-up" and at this point the young fish ceases to be described as an "alevin" and is described as a "fry". Shortly after swim-up the fry leave the immediate vicinity of the redd and adopt individual feeding stations and territories; the fry are then termed "parr" (Plate 2).

The speed at which the eggs and alevins develop is mainly controlled by temperature, though other factors such as low oxygen concentration and mechanical shock can have some influence. At any given constant temperature, if the time from egg laying to hatching is taken as 100%, then the times to median eyeing and swim-up are about 50% and 170% respectively.

Fig. 2 shows the approximate time, in days, taken from the time of laying to the time of hatch for trout and salmon eggs at different temperatures. At any given temperature, salmon eggs take rather longer to hatch than trout eggs. If daily mean water temperatures are available for the stream containing the redds, they can be used to predict median times of eyeing, hatching and swim-up for each fish species. These predictions are for *median* development times, where half of the eggs are expected to reach eyeing, hatching or swim-up respectively (Crisp 1992).

As will be seen later, the ability to predict development times is an important first step in assessing periods of risk for these stages. The predictions will usually be accurate to within 1-2 weeks. However, these are predictions of "average" (median) dates. Within any given batch of eggs some will develop faster and some slower than average, so that hatching of the whole batch may cover a period of several weeks. It is also important to note that water temperature can vary along the length of a stream and that is also varies during the course of each day at any given point in the stream. Temperatures should, therefore, be measured close to redds and, if possible, at least twice each day (e.g. at 0900 and 1500 hours).

Free-swimming stages

The free-swimming stages of salmonids require clean, well oxygenated water, an adequate food supply, space and cover (hiding places). At most stages and in most conditions the fish are territorial. Parr compete with one another for feeding/living territories and mature fish compete for spawning sites.

Feeding and growth are largely controlled by temperature. The relationship between growth rate and temperature differs between species, as do water velocity preferences.

Some trout remain close to their place of birth throughout their lives, whilst others, when a few years old, become smolts and go to sea, but return later (usually to the stream in which they were reared) to spawn. These two strategies are merely the extremes of a wide range of patterns of migration. In general, females tend to move downstream more readily and for longer distances than males. Most salmon go to sea, though some male parr may become sexually mature and take part in spawning before going to sea. Salmon, also, usually "home" and try to return to spawn in the stream of their birth.

Environmental requirements, limits, and water velocity

The environmental needs of different life-stages of salmonids are described in quantitative terms, where this is possible. At various points in the text, water velocity is mentioned, and this needs some explanation. Within a given stream section, water velocity close to the bed is usually less than that in mid-water or at the water surface. Research has shown that the velocity at 0.6 of depth (for example, in water 1 m deep, a point which is 60 cm below the surface and 40 cm above the bed) is a good estimate of the average velocity over the whole depth profile. Therefore, velocity at 0.6 of depth is used as a standard but it should be noted that this velocity is usually greater than that experienced by a fish stationed close to the streambed.

Some of the environmental requirements or limits vary with fish size and are, therefore, best defined in terms of fish body lengths.

Environmental requirements and limits of spawning sites

The first attribute of a fish spawning site is that adult fish must be able to gain access to it. Such access can be prevented by natural or man-made obstructions. The latter may be physical (e.g. dams, weirs) or chemical (e.g. polluted estuaries).

The second requirement is for clean, well oxygenated, running water. Although salmon and trout will attempt to spawn in still water, they show a preference for sites where water velocity at 0.6 depth exceeds 15 centimetres per second but is less than 2 female body lengths per second. Salmonids can be seen spawning with their backs above the water surface but they generally prefer water deeper than their own body depth (i.e. deeper than about 0.2 body lengths).

The third requirement is for suitable gravel-beds. Salmonids will use a wide variety of gravel compositions but the ideal is clean gravel of 20-30 mm mean grain size, with less than 15% fine sediment (see below). The area occupied by a typical redd is oval, approximately 3.5 times the body length of the female fish on the long axis parallel to the streamflow, and 0.3 to 0.6 body lengths wide on the short axis at right angles to the streamflow. There is appreciable variation in the shape and area of redds but the above values give a good general guide to the area required. The burial depth of the eggs varies from ca. 0.4 body lengths for a 20-cm female fish to ca. 0.3 body lengths for a 70-cm female, though there is considerable variation around these average values. Therefore, gravel depth ideally should be at least equivalent to 0.4-0.5 female body lengths, though shallower depths may be tolerated. An additional requirement is that the pattern of intragravel flow must satisfy the female fish. At various times while she is digging the redd, the female salmonid uses her anal fin to investigate the water flow at the bottom of the pit. Opinions differ about the exact cues required to satisfy the female fish so that she proceeds to lay eggs, but it is generally agreed that she is testing the adequacy of the flow through the gravel. This, as will be seen later, is important for survival of the eggs and alevins.

The upper reaches of gravel-bedded streams and rivers, in their natural state, are composed mainly of a succession of pools connected by rapids or riffles. Redds are located, typically, in banks of gravel at the lower ends of pools where the water velocity is increasing prior to entering a riffle. At places such as this a good flow of water through the gravel pores might be expected.

The maximum size of the gravel in which a fish can spawn is likely to be limited by her size. An approximate guide is the equation: P = 0.5/. + 4.6, where *P* is median grain size (mm) and *L* is fish length (cm). This implies that the coarsest gravel in which a 20-cm fish can spawn will be about 15 mm in median diameter, whilst the value for a 70-cm fish will be about 40 mm. This is only a very approximate guide and two points must be noted. First, it is an upper limit and, for example, a 70-cm fish may choose to spawn, or may be obliged to spawn, in much finer gravels than 40 mm median grain size. Second, the value of *P* refers to median grain size and a fish of 20-cm length may be able to spawn in gravels with some particles appreciably larger than 15 mm, provided the median value is less than 15 mm.

[Sedimentologists describe gravel size in various ways, although none of them gives a complete description of gravel composition. One of the commoner measures is "median grain size". A gravel sample is dried and passed through a series of standard sieves of decreasing mesh size. The weight of material which passes through each successive sieve is determined. The median grain size is calculated as the mesh size through which exactly 50% of the sample, by weight, would have passed, had that mesh size been used.]

Environmental requirements and limits of intragravel stages

Once it is buried in the gravel, the egg is unable to move about and its fate is, therefore, heavily dependent upon the choice of spawning site made by the female parent. The egg depends upon the seepage of water through spaces in the gravel to convey oxygen to it and carry away toxic waste products (especially ammonia).

Flow through the gravel, in its turn, is determined by the streamflow and stream geometry (pools and riffles) and by the shape and size composition of the gravel. The rate of supply of oxygen depends upon the flow through the gravel and also upon the oxygen concentration of the water within the gravel. In addition the rate of egg development and the rate of oxygen uptake of the embryo are influenced by temperature. These interrelationships are complex and at present they can not be adequately defined quantitatively. However, the general principles are clear and the critical importance of water flow through the gravel to the eggs and alevins cannot be overemphasised.

Salmonid eggs and alevins can tolerate dissolved oxygen concentrations as low as 5 milligrams per litre. However, the eggs and alevins consume oxygen and will use up all the oxygen close to them unless there is sufficient flow through the gravel to replenish the water surrounding them. Organic matter in the gravel, such as decomposing debris, also consumes oxygen. Two further points should be noted. (1), At any constant temperature the oxygen requirements of the embryo are at a maximum just before hatching. (2), The alevins differ from the eggs in that, to a certain limited extent, they are able to move about within the gravel and so, in theory, might be able to move to more suitable places within the gravel; but we do not yet know how much they actually do this.

Many attempts have been made to quantify the relationship between gravel composition and the survival of the intragravel stages, but the findings are confused, partly by the use of a wide variety of ways of measuring gravel composition and defining "fine" material, and partly by variation in the design of the biological aspects of the studies. The balance of information available suggests that survival from fertilisation to swim-up can be between 90 and 100% in well-run hatcheries and at good field sites. However, increases above 10-15% in the percentage (by volume) of "fines" (particles smaller than about 1.0 mm diameter) in the gravel may lead to much lower survival rates.

Excessive quantities of silt can act directly upon the young stages by settling on egg surfaces and reducing their oxygen intake or by choking the gills of alevins. Fine particles also have an indirect effect by obstructing the spaces within the gravel and, thus, reducing the flow of water through the gravel and impeding the emergence of alevins at the time of swim-up.

Salmonid eggs do not survive to hatch when pH is below 4.5 or above 9.0. The lower (acidic) end of this range is of most practical importance. Atmospheric pollution from the burning of fossil fuels contains strong acids. These enter fresh waters directly as rainfall or through deposition of dry material on vegetation. The rate of collection of such materials by coniferous forests is particularly high. In waters which contain appreciable concentrations of alkaline materials such as calcium carbonate, these materials neutralise the acid. Where the waters are soft and contain little neutralising material the acids remain and give rise to low values of pH. These can have direct effects upon fish. For example, at pHs below 4.5 the enzyme which weakens the egg shell fails to work and hatching is not possible. There is also an important indirect effect. Aluminium is a very common element in nature and is a major component of clay. At most natural values of pH this alumium is in a comparatively inert and harmless form. However, at low pH values it may enter solution and change into a different chemical form which can be highly toxic to all stages of fish.

We have already seen that the rate of development of eggs and alevins is governed largely by temperature (Fig. 2). Temperature also has considerable influence upon the number of eggs surviving to hatch. More than 95% of trout eggs survive at temperatures between 0 and 10°C, but less than 50% survive at temperatures above 12°C and none survive at temperatures above 15.5°C. The values for salmon are probably similar but the upper limit is likely to be a few degrees higher than for trout.

Soon after they have been laid, salmonid eggs become sensitive to mechanical shock (impact or vibration) and they are readily killed by this means. There is a short initial period of low sensitivity but opinions differ as to whether this period lasts for a number of hours or only for a few minutes. At the most vulnerable stage, up to 50% mortality can be caused by the simple process of drifting 10 metres along a stream channel. Sensitivity to shock reduces considerably after eyeing. Eggs and alevins may be damaged by washout in spates (deeper burial gives increased protection and larger fish bury their eggs more deeply than smaller fish), by asphyxiation through the deposition of suspended solids and, possibly, by exposure to freezing or drying during low flows.

Environmental requirements and limits of free-swimming stages

The rate of growth is influenced by temperature (Fig. 3). For trout, growth is negligible below 4.0°C and the optimum range for growth is about 13-14°C. Salmon show negligible growth below 7.0°C and the optimum range for growth is 16-17°C. Above 19.0°C trout cease to feed and become increasingly stressed; their upper thermal limit is between 21 and 25°C. Salmon show signs of stress at about 22.0°C and the upper lethal limit is 25-28°C. The lower limit for both species is below 0°C. The minimum required oxygen concentration is 5.0-5.5 mg per litre but should, ideally, be above 80% saturation (see Table 1 for details). Fish that are feeding require more oxygen than resting fish, and oxygen requirements are likely to be high during upstream spawning migration.

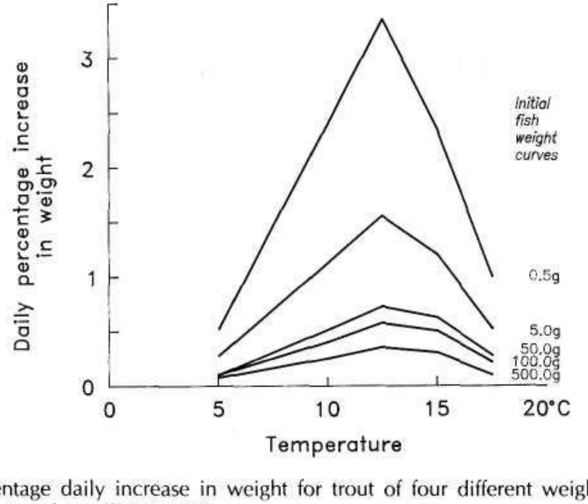

FIG. 3. Percentage daily increase in weight for trout of four different weights at various temperatures. Based on Elliott (1975).

Table 1. Dissolved oxygen concentration at 80% air saturation at five different temperatures.

Temperature (°C)	*Dissolved oxygen concentration ($mg\ l^{-1}$) at 80% air saturation*
0	11.8
5	10.2
10	9.0
15	8.0
20	7.3

Trout require pHs between 4.5 and 9.2, though pH values above 4.5 can be lethal when associated with elevated concentrations of some forms of aluminium and/or other toxic substances. Requirements for salmon are not precisely known but are probably very similar.

High concentrations of suspended solids can harm free-swimming salmonids by clogging and damaging the gills. A European Community Directive specifies an average value of 25 mg per litre of suspended solids as a maximum acceptable concentration, but Alabaster & Lloyd (1982) suggest that less than 25 mg per litre is ideal and 25-80 mg per litre is acceptable.

Juvenile trout prefer water depths of more than 20 cm and velocities of 25 cm per second or less at 0.6 depth. Young salmon avoid low velocities (below 15 cm per second) and prefer depths of less than 20 cm. These preferences give rise to overlapping distributions of juveniles of the two species, with salmon predominant in areas of rapid, shallow flow, and trout predominant in areas of deeper, slower flow. However, both species require space in which to establish feeding stations and individual territories.

Territory size is influenced by a number of factors, including the roughness and irregularity of the streambed, because fish accept smaller territories if the bed is irregular, making their neighbours less visible. Young salmonids also require places in which to hide when frightened. Such places are furnished by irregularities of the streambed and banks, undercut banks, large boulders, fallen branches and similar features. "Natural" streams have a greater capacity to support young salmonids than streams which have been organised and sanitised by levelling their beds, straightening banks, removing bushes and occasional trees, and removing large boulders.

Swimming speeds and the effects of water flow and velocity

The maximum swimming speeds of fish depend chiefly upon temperature and fish size. Two such maximum speeds can be defined. The first is the

. maximum speed at which the fish can cruise for long periods without incurring an oxygen debt. This can be called the maximum sustainable speed (V_{sust}). The second is the maximum speed which can be attained in short bursts but can only be maintained briefly (V_{max}). The maximum sustainable speed can be estimated from the equation: $V_{sust} = (0.32T) \times L^{0.6}$, where T is temperature (°C) and L is fish length (cm). The maximum burst speed can be estimated from: $V_{max} = V_{sust}$ $(1.664\,T^{0.2531})$.

Calculated values of V_{sust} and V_{max} for salmonid fish of three different lengths over the temperature range 0.5-15.0°C are shown in Fig. 4. It is important to note that the equations used here are simplifications of more complex equations given in the literature. Nevertheless the values in Fig. 4 give a fair indication of swimming speeds attainable by fish of different sizes. The estimates of V_{sust} are useful in estimating the likely migration speeds of fish of different sizes at various temperatures, after making due allowance for any help or hindrance provided by water currents. Estimates of V_{max} are helpful in assessing the ability of fish of different sizes to ascend natural and man-made rapids at any given temperature, or for assessing the effects of man-made changes in temperature on the ability of salmonids of given size to cope with such obstacles. Salmonids can negotiate some rapids, water flowing over inclined surfaces, and weirs, by swimming over them at high speed. Knowledge of the water velocity at such places can be used, in conjunction with values of V_{max} to assess the sizes of fish likely to be able to pass a particular obstacle. Some falls are surmounted by leaping, and salmon can leap up to 12 ft (3.7 m). However, the conditions required for successful leaping are complicated. The fish usually leap from somewhere near the crest of a standing wave at the foot of a water-fall and, ideally, the pool at the base of the fall should have a depth of 1.25 times the height of the fall. Beach (1984) deals with the problems of man-made obstructions and with the provision of fish passes.

Upstream and downstream movements and migrations

Upstream movement occurs mainly when the flow is somewhat higher than average, but not at extreme values. In rivers in Lancashire this can be quantified in terms of river flow (cubic metres per second) per metre of river width. At 0.03 $m^3\,s^{-1}$ per metre width the fish are inactive. Upstream movement of fish reaches a peak at flows of 0.08 to 0.2 $m^3\,s^{-1}$ and is reduced again at flows above 0.2 $m^3\,s^{-1}$ per metre width. These values appear to be approximately applicable to rivers elsewhere. There is some evidence that there may be a preferred temperature range for upstream migration, and migration may be stimulated by darkness or by turbid water. Upstream movement is inhibited at temperatures above ca. 22°C or below ca. 5°C.

Upstream migration occurs in a series of stages which depend upon the occurrence of suitable flow conditions. Between stages the fish require deep pools in which to rest, preferably with some cover (such as undercut banks) in which to hide and also to avoid strong sunlight. Homing to a particular tributary within a river system depends mainly upon the sense of smell, though an element of "trial and error" is also apparent.

The seaward migration of salmon smolts is reduced or inhibited below a certain temperature. The exact temperature value depends upon previous temperatures experienced by the fish but is generally around 11 °C. If a similar temperature "trigger" exists for trout smolts then it is likely to be rather lower than that for salmon. The journey to the sea is accomplished mainly at night and is achieved partly by passive downstream drift and partly by active swimming. During their downstream run the smolts may risk being drawn into the intakes of turbines, power stations and industrial cooling systems. Detailed treatment of the problems and possible solutions is given by Turnpenny (1988).

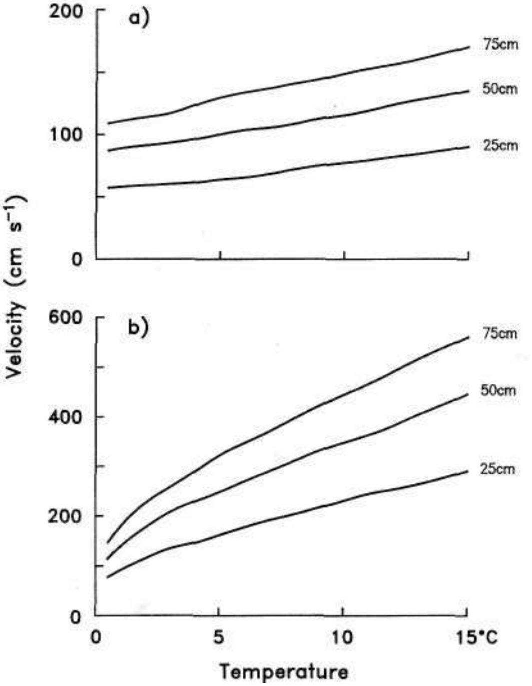

FIG. 4. Relationships between (a) sustainable swimming speed (cm per second) and water temperature, and (b) maximum swimming speed and temperature, for salmonid fish of three different body lengths.

Mixed populations and carrying capacity

There is little detailed information on the interactions of young salmon and trout in mixed populations, though when the two species do occur together in the same reach of river it is likely that substantial segregation of the two will occur on a microhabitat scale, as a consequence of differing depth and velocity preferences. We have already noted that the young of each species compete with one another for territories and, when necessary, this competition will ensure that population densities are reduced to match the "carrying capacity" of the habitat. The carrying capacity will vary between streams, largely as a function of differing productivity and available cover, and may also vary somewhat from year to year within any given stream. In particular, the carrying capacity of a unit length of any given stream will vary with the flow. At low flows, whether of natural occurrence or through human intervention by drainage or abstraction, the area of water will be reduced and the number of fish which it can support will be correspondingly less.

Acceptable population densities of salmon and trout parr vary from about 2 to 10 per square metre in spring, but fall to half these values or less by the autumn, as the fish grow and their territory sizes increase. The important practical point is that, in any given stream, there will be an optimum stocking density and attempts to artificially stock much above this level are likely to be counterproductive. However, where population densities are demonstrably sub-optimal, artificial stocking may be of value.

Human impacts upon salmonids

Man can influence fish and their environment in a wide variety of ways. Some of the main ones are shown in Fig. 5, but many more activities and consequences could be listed. Particular points to note are the following.

(1). Any given example of a particular activity does not necessarily lead to all of the possible consequences listed against it in Fig. 5. For example, some industrial effluents may modify the temperature of the water but not its pH, dissolved oxygen or content of toxic materials, whilst other industrial effluents may contain toxic substances but may not alter the water temperature.

PLATE 1. *(Facingpage 188).* Salmonid eggs. *Top left:* dead eggs. *Top right:* living eggs; one is at an early stage of development and the other is "eyed". *Middle:* eyed eggs with the embryos clearly visible. *Bottom:* an alevin in the process of hatching from the egg. The diameter of the eggs is ca. 5 mm. Photographs by Trevor Furnass, ARPS.

PLATE 2. *(Facing page 189).* Salmonid alevins and fry. *Top:* a recently hatched alevin with a large yolk sac. *Middle:* an older alevin with a partly absorbed yolk sac. *Bottom:* a fry or parr shortly after emerging from the gravel. The body lengths of these stages are 20 to 25 mm. Photographs by Trevor Furnass, ARPS.

ACTIVITY	Discharge	Water velocity	Temperature	pH	Dissolved oxygen	Bed movement	Siltation	Toxicity	Suspended solids	Eutrophication	Mechanical shock	Obstruction of movement	Genetic change	Overstocking	Diseases	Introduction of exotics	Overfishing	Direct mortality
Fish cropping																	●	
Fish farms	●	●		●	●		●	●	●	●			●		●	●		
Fish stocking													●	●	●	●		
River impoundment	●	●	●		●	●	●		●			●						
River regulation	●	●	●		●	●	●		●			●						
River transfer	●	●	●		●	●	●		●			●						
Abstraction	●	●	●		●	●	●		●			●						
Land drainage	●	●				●	●		●									
Channel dredging						●	●				●							
Farm and forest effluent				●	●		●	●	●	●								
Sewage effluent				●	●		●	●	●	●								
Industrial effluent			●	●	●		●	●	●	●								
Extraction of gravel and sand						●	●		●		●							
Changes in bank vegetation	●	●	●	●														
Changes in aquatic vegetation		●		●	●				●			●						
Roads						●	●	●	●		●							
Vehicles						●	●		●		●							
Entrapment of fish in off-takes, turbines etc.																		●

FIG. 5. List of human influences and some of their possible consequent effects upon the aquatic environment or directly upon fishes.

(2). Some important human activities may be composites of two or more of the activities listed in Fig. 5. Thus agriculture may involve some or all of the following: abstraction (for irrigation), land drainage, passage of vehicles through streams, changes in bank vegetation, fertilisers, pesticides and farm effluents.

(3). Some of the activities may imply or lead to more severe problems. For example, excessive and/or inept land drainage schemes can lead to extensive and irreversible land erosion.

Man's most direct effect on salmonid populations is through cropping by legitimate means, such as licensed rod-fishing for sport and licensed commercial fishing by nets and/or "fixed engines", and by a variety of illegitimate methods which can be broadly described as "poaching". The dangers of overfishing are self-evident and it is in the interests of all riparian owners and anglers to press those in authority to hasten the realisation of two important objectives. The first is an adequate enforcement of existing rules and laws aimed at *protecting the stock.* The second is *collection of sound scientific data on stocks and population dynamics,* so that the maximum sustainable yield of each salmonid fishery can be estimated and the stock can be defined and appropriately apportioned between commercial fisheries, sport fishing, and fish allowed to run upstream for reproduction. This must be a long-term aim, but it is of great importance. Efficient and accurate automatic fish counters and competently organised tagging programmes could make a major contribution to the assessment of stocks.

Impact of fish farms and hatcheries

The rearing of fish in hatcheries and fish farms is a form of intensive culture, often involving a single species or at most only two or three species of fish. The installations usually abstract water from springs and streams and then release effluent to the same stream. The abstraction point is normally upstream of the release point, and where the abstraction is large relative to streamflow, the portion of stream between the points of abstraction and release may have a much reduced discharge (volume of flow per unit time) and water velocity. The effect can be so extreme that it obstructs the upstream movement of fish on their way to spawning grounds and some may enter the intakes of the hatchery or fish farm.

Effluents from these intensive units may differ from the natural stream water by having a modified temperature and pH, and they may be contaminated with toxic materials used to disinfect hatchery equipment. In addition, the effluents often carry waste and partly decomposed food, and the metabolic products of the fish. These can lead to increased oxygen demand (and hence a low oxygen concentration in the water), increased suspended solids, and enrichment (eutrophication) of the recipient stream. When fish-rearing facilities are being set up it is important to ensure that the abstraction of water is reasonable, relative to dry weather discharge of the stream, and that the effluents will be of satisfactory quality at all times.

An inevitable feature of fish farms and hatcheries is the frequent transportation of fish into and out of the unit. This gives a rather high risk that diseases will eventually occur, spread rapidly and reach the wild salmonid population in the stream or river. Some fish inevitably escape, even from the best-managed hatcheries, and often the losses by escape are substantial. This can lead to a dilution of the genetic make-up of indigenous populations where the same species are being cultured (see Cross 1989), and also leads to the introduction of exotic species into natural watercourses. The widespread occurrence of rainbow trout in UK waters is almost entirely a result of escapes from hatcheries, fish farms, and stocked waters. Fortunately, in the UK, rainbow trout rarely seem to compete well with the indigenous salmonid species. We may not, however, be so fortunate with future escapes and releases of other exotic species.

The stocking of natural watercourses with farm and hatchery-reared salmonids is widespread and has a long history. In common with fish farming and hatchery operations, this form of stocking also increases the risks of spreading disease and genetic change in the natural population, and increases the risk of introducing exotic species *of* organisms other than fish. Such stocking is likely to be wasteful and counterproductive if practised in waters which are already well stocked with fish. It can, however, have value in ensuring the full utilisation of waters that are inaccessible for natural spawning, in maintaining stocks in heavily exploited fisheries, and in re-establishing populations which have been destroyed by pollution incidents and similar mishaps. An excellent practical guide on salmon stocking is given by Egglishaw et al. (1984) and similar principles should be followed in trout stocking.

Impact of changes in flow regime

The natural flow regime of a stream or river is influenced by the relief, geology and soil of its catchment, vegetation cover, and climate. Man can alter the natural flow regime by activities such as abstraction, river regulation, river transfer, changes in land use, land drainage and hydro-electric generation, flood protection and urban development (Fig. 6). Where human intervention(s) involve dams or weirs, these may also obstruct the movements of fish. Changes in flow regime can increase or decrease the total annual discharge, or modify the pattern of fluctuations in flow over a period of time, or alter some combination of these variables. The main effects of different types of intervention on flow regime are set out in Fig. 6. These changes in flow regime lead to "consequent physical effects": these are mainly changes in wetted area of the streambed, water velocity, suspended solids, and changes in the rates and locations of bed scour and sediment deposition.

Changes in wetted area may alter the amount of spawning ground available to salmonids and also the area available as a nursery for the young fish. Rapid changes in wetted area (e.g. downstream of a hydro-electric plant) may lead to the exposure of eggs to dessication or freezing, and juvenile fish may become stranded. Modified water velocity alters the availability of spawning ground for salmonids and, via changes in

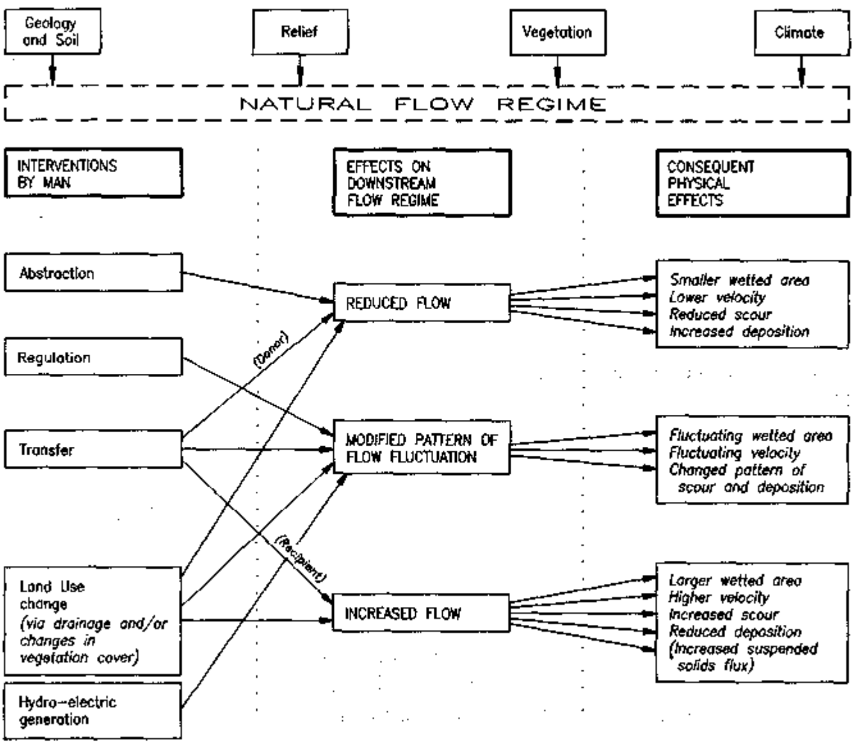

FIG. 6. Simplified summary of the main natural factors influencing the flow regime of a natural river (top) and details of major modifications to the flow regime that can occur as a result of human intervention in the system. Some of the main physical consequences that can result from such intervention are also indicated. After Crisp (1989b).

intragravel flow, it can influence survival of the eggs and alevins. It may also alter the suitability of the local habitat in favour of either young salmon or young trout. An increase or decrease in the amount of bed scour will result in the destruction of more or fewer redds and eggs, and also affect the survival of juveniles. Modified rates of sediment deposition alter the risk of redds being choked by silt, when eggs or alevins are asphyxiated and alevins become trapped at the time of swim-up. The infilling of gravel interstices also reduces the amount of cover available for young salmonids and for their invertebrate prey.

Blanket-bogs on high ground, and other peatlands, act as an important reservoir of water and stabilise the stream flow. Such areas are frequently drained for the purposes of forestry, agriculture and sport. The benefits of this drainage are usually difficult to demonstrate but it certainly increases the speed at which water runs off into streams, and also increases the suspended solids content of waters in spate (flood). Drainage reduces the flow in dry weather. All of these effects can be damaging to salmonids. Similar considerations apply to the harvesting of peat.

Effects of effluents

The term "effluent" is used here not simply with reference to fluid materials that are deliberately piped into water courses but also to materials which are applied to land, plants or animals and/or which escape from containers (pesticide cans, slurry tanks) and which then (by seepage, downwash or other means) reach the watercourses. Each type of effluent can affect salmonid fishes in one or more of six ways.

(1). Organic materials such as domestic sewage, farm slurry, silage liquor and some industrial effluents cause a substantial microbial oxygen demand which depletes the oxygen content of the water, resulting in stress or death of salmonids. It is worth noting that silage liquor has some 300 times the oxygen demand of human sewage!

(2). In addition to their effect in depleting oxygen, these materials may also elevate the concentrations of suspended solids.

(3). Effluents may contain toxic materials. Other industrial effluents (e.g. China clay) may be relatively innocuous in terms of toxicity or oxygen demand, but may still be harmful to salmonids through their effects on suspended solids and siltation.

(4). Inorganic fertilisers can be washed off the land in surprisingly large quantities and, together with nutrients from domestic sewage and some of the decomposition products of organic effluents, they can lead to eutrophication (enrichment) of streams with consequent effects upon aquatic vegetation, including growths of toxic blue-green algae in some lakes.

(5). Changes in water pH and miscellaneous forms of toxicity can arise from some industrial effluents, from pesticides applied to trees and crops or to animals (e.g. sheep dip) and from other sources. Even nitrate from fertilisers can be toxic if it is reduced to nitrite. It is also important to note that the solvents and carriers in some pesticides can be almost as harmful as the "active" ingredient.

(6). Some industrial activities produce heated effluents and this modifies the temperature regime of a portion of the recipient watercourse.

Impact of changes in land use

Changes in vegetation adjacent to watercourses (described in Fig. 5 as "bank" vegetation) include the ploughing of pasture land, the planting and harvesting of farm crops and the replacement of pasture or moorland by forest. Such changes in the amount and type of vegetation cover may lead to changes in the temperature regime and aquatic vegetation of the watercourse and also to changed availability of aquatic and terrestrial invertebrates as food for fish. Perhaps the most extreme form of this is afforestation with conifers, which can also influence water pH. The management activities necessary to bring about these changes in terrestrial vegetation often entail land drainage, application of pesticides, fertilisers and other materials (see above).

The development of buildings and roads can lead to increased run-off, and also to an increased risk of pollution and release of suspended solids, both during construction and during occupation.

Judicious planting of bankside trees (especially deciduous species) can provide useful shade and some cover from roots which grow into the water, though intensive culture of conifers close to the water's edge can be harmful.

Changes in aquatic vegetation may involve changes in quantity and/or species composition. These effects may arise from natural successions of plant communities (often accompanied by silting up of the watercourse), from loss of plants through deliberate or accidental applications of herbicides, and through increased plant growth as a result of enrichment by, for example, agricultural fertiliser from adjacent land. The type and quantity of aquatic vegetation influences water velocity, pH, daily dissolved oxygen fluctuations, suspended solids, and cover for invertebrates. Very dense growths of plants may obstruct fish movements. In some watercourses regular weed cutting and/or dredging may be necessary. However, it is important that the work should be done in moderation, and cut weed should be removed from the water. Large accumulations of rotting weed can lead to lack of oxygen.

Effect of roads and vehicles

This broad topic can be considered in terms of the impact upon the aquatic environment of (a) the construction and use of roads, (b) the use of off-road vehicles, and related activities.

Simple unsurfaced farm and forestry roads, particularly during and soon after construction, can be a source of suspended solids in streams (Fig. 7). Indeed, if not carefully constructed and sited, they can, in some upland areas, lead to continuing problems of land erosion. Indiscriminate abstraction of gravel from stream and river beds, and banks, for use in stabilising unsurfaced roads, can cause instability of the stream/river bed or banks with consequent deleterious effects upon salmonids. The construction of surfaced roads (and other building and civil engineering activities) can lead to harmful releases of cement liquors and noxious phenolic compounds from road-surfacing materials, and can also increase the rapidity of run-off into watercourses. The effluents from public roads are sometimes deliberately routed into watercourses, often underneath road bridges. These effluents can carry into streams appreciable quantities of suspended solids and, in wintertime, solutions of salt and other de-icing materials.

Management of rivers and streams, and adjacent land and ditches, may necessitate the deployment, from time to time, of machines such as tractors, diggers, draglines and weedcutters. These vehicles may travel alongside streams, across streams or even along the streambed (Fig. 8). Mud from their wheels and tracks may add to the load of suspended solids. When operating in or close to the stream they may stir up silt, and they may also disturb and/or impart mechanical shock (pressure, impact, vibration) to gravel-beds harbouring eggs and alevins. It is, therefore, important that instream works such as dredging, weed cutting and channel modification should be carried out with due regard to the life cycle of salmonids and preferably so as to avoid that period of the year when local gravel-beds are likely to contain young stages.

Instream works

Population densities of salmonids are influenced by the spatial and physical variability of their habitat and particularly the amount of available cover. Good husbandry and the need to prevent floods may demand some tidying-up of streams and their banks. However, it should be recognised that over-enthusiastic clearing of obstructions, removing undercut banks, straightening the streamcourse or dredging-out the streambed — both of which destroy the natural sequence of pools and riffles — will lower the quality of the stream as a salmonid habitat.

FIG. 7. The confluence of two streams, showing one (bottom) laden with suspended solids (sediment) from construction work upstream. Suspended solids can be lethal to salmonid eggs and fry, and spoil the spawning grounds when deposited in small spaces between gravel.

FIG. 8. A tractor and trailer driven over gravel-beds in shallow water can damage the spawning grounds of salmonids and may destroy developing eggs..

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